# EFFECTS OF ENVIRONMENTAL VARIABLES ON PHYTOPLANKTON IN THE COASTAL WATERS OF KALPAKKAM WITH SPECIAL EMPHASIS ON THERMAL DISCHARGE FROM A POWER PLANT, SOUTHEAST COAST OF INDIA

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**Muthulakshmi Alagan**[1]
**Usha Natesan**[2]
**Vincent A Ferrer**[3]
**Deepthi** [3]
**Vayalam P Venugopalan**[4]
[1] University of information science and technology St. Paul the Apostle,
Ohrid, **Republic of North Macedonia**
[2] All India Council for Technical Education, Nelson Mandela Marg, Vasanth Kunj,
New Delhi, **India**
[3] Anna University, Chennai, **India**
[4] Bhabha Atomic Research Centre, Mumbai, **India**

## ABSTRACT

The power plants are mostly located along the coast to make use of large quantities of seawater and heated effluents being discharged into coastal marine environments. Planktonic organisms are drawn along with the cooling water are exposed to various physical and chemical stress, temperature gradients, mechanical stress and antifouling chemicals. During the period of 2011, monthly boat cruises were undertaken in the sea, in an area of about 2.0 km. Based on the impact of thermal effluents, water and phytoplankton samples were collected and analysed near the intake of Prototype fast breeder reactor, outfall of Plutonium recycle project and the mixing point of Madras atomic power station. 29 phytoplankton genera were recorded. Among these 86.2 % of diatoms, 6.9 % of dinoflagellate, 3.5 % of cyanobacteria and 3.5 % of silicoflagellates. Significant changes were noticed according to seasonal variations in phytoplankton genera based on the availability of environmental parameters. Phytoplankton abundance was high in the station P1 than at the station P2. Our results suggest that thermal discharge may affect the phytoplankton distribution and abundance within a restricted area close to Madras atomic power station condenser outfall and quite localized, whereas the coastal ecosystem is not affected. Temperature, salinity, dissolved oxygen and chlorophyll-a played a significant role in phytoplankton abundance.

**Keywords:** Physico-chemical parameters, phytoplankton, Kalpakkam, power plant, thermal effluents, canonical correspondence analysis

## INTRODUCTION

Coastal environments are often used as a disposal zone for thermal wastes from the cooling processes in thermal or nuclear power plants. As seawater-cooled plants are generally operated in a once-through mode and continuously discharged into the coastal water body [1]. The condenser effluents from power plants have the potential impact of thermal and chemical stress and, therefore, may pose environmental problems to the receiving water body [2]. Since, temperature being a very important ecological parameter is essential for the metabolic rate of organisms and the levels of dissolved oxygen [3] and [4], changes occur in the marine environment due to the disturbance of ambient temperature [5], [6] and [7]. The power plant thermal discharges can change microbial habitats in the immediate mixing with the coastal water zone [8].

The phytoplankton perform a vital role in marine food webs, about 90% of the total production is contributed by the phytoplankters in marine ecosystem. It also acts as most important primary producer in food webs that supporting commercial fisheries [9] and [10]. The phytoplankton biomass helps to understand the water quality and eutrophication of particular area [11] and [12]. Phytoplankton helps to convert inorganic compounds in to organic compounds by photosynthesis process using solar energy. The phytoplankton structure may affect by risky changes in hydrographic conditions, because these communities are more sensitive to environmental variations [13]. The present study was undertaken in the vicinity of the Madras Atomic Power Station (MAPS), which uses the coastal waters of the Bay of Bengal as a heat sink. It was hypothesized that the continuous discharge of condenser effluents may have an impact on the ecology of the coastal environment and a study was organized to understand the influence of the discharge on the phytoplankton population near the discharge zone. The objectives of this study were (1) to determine the potential effect of thermal discharges on abundance and distribution of phytoplankton between intake and mixing regions, and (2) to compare the relationship between phytoplankton communities and environmental variables.

## MATERIALS AND METHODS

### Study area

MAPS is located in Kalpakkam (12°33”N and 80°11”E), southeast coast of India, about 70 Km south of Chennai. MAPS consist of two units of pressurized heavy water reactors (PHWR) with an installed capacity of 220MWe each, down rated to 170MWe each. The power plant use $35m^3/s^{-1}$ of seawater for cooling. The main condenser of each unit is designed for a $\Delta T$ (temperature difference between inlet and outlet) of 10°C. From the outfall point, the discharged seawater flows through the engineering canal (~0.98 km) before it mixes with the sea. The existing MAPS discharge is 35 m3/s, a new 500 MWe power plant, Prototype Fast Breeder Reactor (PFBR) 680m south of the existing MAPS is proposed with the cooling water requirement of 29 m3/s. According to the climatology of this coastal area the whole year has been divided into four seasons viz: (1) post-monsoon (January–March), (2) summer (April-May), (3) southwest monsoon (SW) (June–September), and (4) northeast monsoon (NE) (October–December). The NE monsoon is active in this area and bulk (80%) of rainfall occurs during this period. Due to the geographic location of this area, the monsoon reversal of wind and the subsequent change in the current pattern is prominent here leading to a visible alternation of the coastal milieu.

### Sampling strategy

A typical sampling design is illustrated in Figure 1, to understand the environmental variables and phytoplankton community, monthly samples were collected from 200m south of near PFBR (station P1), Plutonium Recycle Project outfall in MAPS Engineered Canal (station P2) and near MAPS mixing point (station P3) (Table 1).

## Physico-chemical parameters

Environmental variables such as suspended particulate matter (SPM), dissolved oxygen (DO) and chlorophyll-a (Chl-a) were analyzed according to standard method described by Strickland and Parsons [14] and Grasshoff et.al. [15]. pH was recorded with pH meter (WTW, Germany) with a resolution of 0.01. Surface water temperatures were recorded using standard mercury filled centigrade thermometer. Salinity and turbidity were recorded with the WTW 330i probe and turbidity meter (CyberScan IR TB 100), respectively.

**Table 1.** Plankton sampling stations

| Station ID | Latitude N | Longitude E | Area Description |
|---|---|---|---|
| P1 | 12°32'49.263" | 80°10'44.857" | 200m south of near PFBR intake |
| P2 | 12°33'42.811" | 80°10'47.06" | Plutonium Recycle Project outfall in MAPS Engineered Canal |
| P3 | 12°33'54.735" | 80°11'8.038" | Near MAPS Mixing Point |

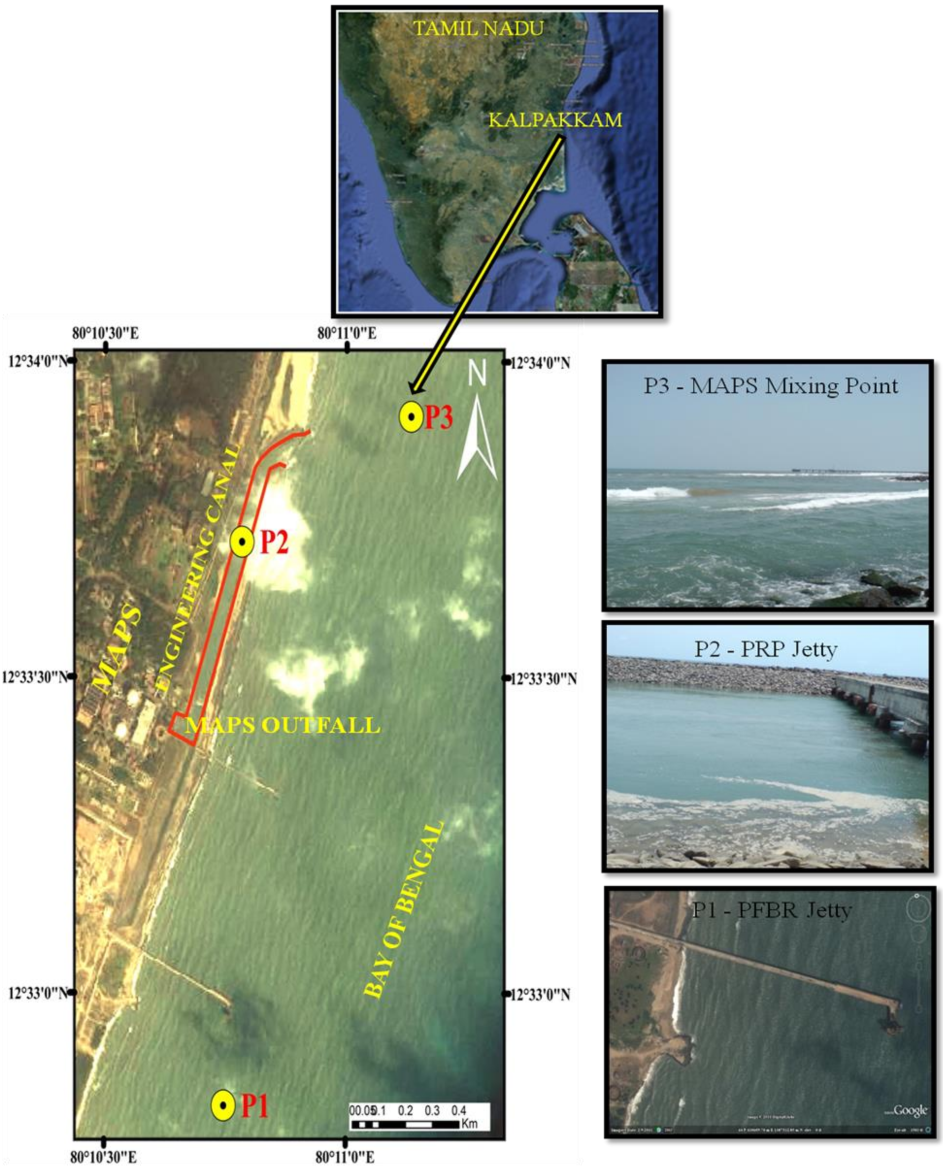


**Figure 1.** Study area and sampling locations

### Physico-chemical parameters

Environmental variables such as suspended particulate matter (SPM), dissolved oxygen (DO) and chlorophyll-a (Chl-a) were analyzed according to standard method described by Strickland and Parsons [14] and Grasshoff et.al. [15]. pH was recorded with pH meter (WTW, Germany) with a resolution of 0.01. Surface water temperatures were recorded using standard mercury filled centigrade thermometer. Salinity and turbidity were recorded with the WTW 330i probe and turbidity meter (CyberScan IR TB 100), respectively.

### Phytoplankton

Phytoplankton samples were collected at monthly intervals, for qualitative and quantitative studies of phytoplankton, 50ml of sample was concentrated from 10L of surface water sample collected and fixed with 5% formaldehyde solution. From the above concentrated sample, 1ml was taken on a Sedge-wick Rafter cell for analysis under a Carl Zeiss compound microscope for counting. Identification of phytoplankton was done by following standard taxonomic monographs for diatoms [16], dinoflagellates [17] and [18] and green and blue-green algae (Cyanobacteria) [19].

### Data analysis

The differences in environmental variables, abundance and genus richness were confirmed by bar graph. CANOCO 4.5 version software was used for Canonical Correspondence Analysis (CCA) [20]. Phytoplankton communities with environmental variables were linked by the CCA plots using CANOCO.

## RESULTS

### Physico-chemical parameters of water

Throughout the study period, pH remained alkaline with fluctuated from 8.0 - 8.4, surface temperature from 27.2°C to 36.0°C, salinity from 30.0 to 33.4 psu, turbidity from 0.9 – 12.2 NTU, SPM from 18.4 – 75.0 mg/L, DO from 3.7 – 6.3 mg/L and Chl-a form 1.2 – 3.2 mg/m3 (Table 2). Highest salinity was recorded during summer and the lowest in northeast monsoon in all three stations. Monthly values showed relatively high-water turbidity at station P1 during June and August and not much variation was noticed during the rest of the study period (Table 2). The station P2 showed marginally higher turbidity compared to the other two locations, due to shallow water depth.

Temperature varied from 27.2°C to 31.1°C at station P1, whereas station P2 observed from 30.3°C to 36°C. At the end of the discharge canal (0.98 km length), where the effluents mixed with the sea, the temperature varied from 27.5°C to 31.4 °C at station P3. Table 5 gives details of the power plant operation and $\Delta T$ (with respect to the intake water) during January –December 2011. The mean ambient seawater temperature at the study site is about 28°C. Temperature at MAPS condenser outfall during this study period was about 8.4–9.3 °C greater than that at the intake, when the two units were operational (Table 3). A lesser $\Delta T$ magnitude of 1.9–5.8 °C (with respect to the intake water) was recorded at the mixing point (P3).

Table 2 shows that chlorophyll-a level at station P1 and P3 were comparable indicating the substantial recovery of phytoplankton. The chlorophyll-a level at station P2 was slightly less than that at station P1, the loss being attributable to grazing inside the intake tunnel. The elevated level was noticed during September and decreased during northeast monsoon. Variations in dissolved oxygen show similar pattern in the sampling stations with high levels in June (6.3 mg/L at P1 and 5.8 mg/L at P3). Thermal discharge from the power plant did not affect the distribution of physico-chemical parameters in the study area.

**Table 2.** Monthly variations in environmental variables at station P1, P2 and P3

| Months | Environmental Variables | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | pH | Temperature (°C) | Salinity (PSU) | Turbidity (NTU) | SPM (mg/L) | DO (mg/L) | Chl-*a* (mg/m$^3$) | |
| **Jan** | 8 | 28 | 31.2 | 4.5 | 30 | 4.5 | 2.1 | **Station P1** |
| **Feb** | 8.1 | 27.3 | 32.3 | 3.4 | 36.4 | 4.2 | 2.7 | |
| **Mar** | 8 | 28.1 | 31 | 1.2 | 18.4 | 4.5 | 2.4 | |
| **Apr** | 8.3 | 29.4 | 32.6 | 1.6 | 40.4 | 5.2 | 2.2 | |
| **May** | 8 | 31.1 | 33 | 5.3 | 56 | 4.5 | 1.9 | |
| **Jun** | 8.3 | 28.7 | 32 | 12.2 | 75 | 6.3 | 2.6 | |
| **Jul** | 8.4 | 28 | 30.7 | 2.2 | 44.8 | 4.5 | 2.8 | |
| **Aug** | 8.4 | 28 | 30.8 | 10.1 | 71.6 | 5.2 | 2.3 | |
| **Sep** | 8.4 | 27.6 | 30.3 | 0.9 | 36.2 | 4.7 | 3.2 | |
| **Oct** | 8.4 | 28 | 31 | 7.2 | 74 | 5.1 | 2.4 | |
| **Nov** | 8.3 | 28 | 32 | 1.4 | 29.2 | 4.8 | 2.4 | |
| **Dec** | 8.3 | 27.2 | 30.8 | 0.9 | 49.6 | 4.8 | 2.3 | |
| **Jan** | 8.1 | 34 | 31.8 | 6.7 | 48.4 | 4 | 1.2 | **Station P2** |
| **Feb** | 8 | 35.7 | 31.1 | 10.9 | 45.6 | 3.8 | 1.8 | |
| **Mar** | 8.2 | 36 | 30.2 | 3.1 | 27.6 | 4.1 | 1.5 | |
| **Apr** | 8.2 | 36 | 33.2 | 6.8 | 49.2 | 3.7 | 1.6 | |
| **May** | 8.2 | 35 | 32.1 | 1 | 35.6 | 3.9 | 1.7 | |
| **Jun** | 8.1 | 34 | 31.6 | 7.2 | 55.6 | 4 | 1.2 | |
| **Jul** | 8.3 | 34.2 | 31.3 | 3.5 | 56.8 | 4.2 | 1.8 | |
| **Aug** | 8.4 | 35.4 | 30.9 | 5.9 | 62 | 3.9 | 2 | |
| **Sep** | 8.3 | 32.4 | 31.3 | 3.3 | 51 | 4 | 2.2 | |
| **Oct** | 8.4 | 35 | 30.8 | 3.4 | 43.6 | 4.1 | 1.7 | |
| **Nov** | 8.3 | 31.6 | 30 | 1.4 | 34 | 4.1 | 1.4 | |
| **Dec** | 8 | 30.3 | 31.7 | 4 | 50.8 | 4.2 | 1.9 | |
| **Jan** | 8 | 29.8 | 32.1 | 5.5 | 44.8 | 4.8 | 1.4 | **Station P3** |
| **Feb** | 8.1 | 31.4 | 31.9 | 5.9 | 26.4 | 4.5 | 2 | |
| **Mar** | 8.2 | 28.9 | 32.1 | 5.1 | 30.8 | 4.6 | 2.2 | |
| **Apr** | 8.3 | 30 | 32.1 | 2 | 46 | 5.5 | 2 | |
| **May** | 8.3 | 30.6 | 33.4 | 4.9 | 54 | 4 | 1.7 | |
| **Jun** | 8.2 | 28.5 | 32.1 | 5 | 62 | 5.9 | 1.7 | |
| **Jul** | 8.4 | 29.4 | 31.3 | 2.8 | 45.2 | 4.2 | 2 | |
| **Aug** | 8 | 29.6 | 31.8 | 7.1 | 68 | 5.3 | 2.1 | |
| **Sep** | 8.4 | 27.5 | 31.2 | 0.9 | 48.2 | 4.3 | 3.1 | |
| **Oct** | 8.3 | 29.5 | 31.9 | 5.5 | 69.2 | 4.7 | 2.4 | |
| **Nov** | 8.2 | 29.1 | 31.2 | 1.4 | 32.8 | 4 | 2.2 | |
| **Dec** | 8.3 | 28.8 | 31.8 | 3.8 | 38.8 | 5.6 | 2.2 | |

## Phytoplankton abundance and diversity

A total of 29 distinct variation of phytoplankton genera were identified in the present study belonging to diatoms form the most dominant (86.2 %) group followed by dinoflagellate (6.9 %), cyanobacteria (3.5 %) and silicoflagellates (3.5 %). Table 4 to 6 displays the abundant and common phytoplankton distribution recorded during the study period. Noticeable monthly differences in population density of phytoplankton communities ranged from 332-755 cell/ml in station P1, 285-637 cells/ml in station P2 and 323-734 cells/ml in station P3 (Fig. 2). During March, April, May and September observed that richness of phytoplankton communities.

The diatoms formed the dominant group in the present study, Amphipora, Amphora, Asterionellopsis, Bacteriastrum, Biddulphia, Odotella, Chaetoceros, Cocconeis, Coscinodiscus, Cyclotella, Ditylum, Eucampia, Fragillaria, Guinardia, Leptocylindrus, Melosira, Navicula, Nitzchia, Pleurosigma, Pseudonitzschia, Rhizosolenia, Skeletonema, Thalassiothrix, Thalassiosira and Triceratium. Station P1 noticed richer phytoplankton genus and a sudden alteration was observed in station P2, though station P3 shows recovery of genera. Among diatoms, Asterionellopsis, Thalassionema, Biddulphia, Chaetoceros and Skeletonema were found to be dominant. Similarly, dinoflagellate community was dominated by Protoperidinium and Peridinium.

**Table 3.** Details of temperature at MAPS intake, outfall and mixing point during January to December 2011

| Months | Sampling Dates | Intake (°C) | Outfall (°C) | Mixing Point (°C) | Outfall - Intake ΔT (°C) | Mixing Point - Intake ΔT (°C) |
|---|---|---|---|---|---|---|
| **Jan** | 24.01.2011 | 26.5 | 34.9 | 32.3 | 8.4 | 5.8 |
| **Feb** | 23.02.2011 | 28.7 | 37.7 | 33.6 | 9.0 | 4.9 |
| **Mar** | 24.03.2011 | 29.4 | 38.5 | 35.0 | 9.1 | 5.6 |
| **Apr** | 26.04.2011 | 30.1 | 39.4 | 33.0 | 9.3 | 2.9 |
| **May** | 23.05.2011 | 27.8 | 36.6 | 33.6 | 8.8 | 5.8 |
| **Jun** | 20.06.2011 | 28.4 | 37.3 | 32.5 | 8.9 | 4.1 |
| **Jul** | 20.07.2011 | 29.3 | 37.7 | 33.7 | 8.4 | 4.4 |
| **Aug** | 25.08.2011 | 29.2 | 36.2 | 32.7 | 7.0 | 3.5 |
| **Sep** | 16.09.2011 | 27.9 | 36.3 | 33.2 | 8.4 | 5.3 |
| **Oct** | 18.10.2011 | 30.6 | 39.9 | 32.5 | 9.3 | 1.9 |
| **Nov** | 15.11.2011 | 29.0 | 38.3 | 33.8 | 9.3 | 4.8 |
| **Dec** | 20.12.2011 | 27.1 | 36.3 | 32.5 | 9.2 | 5.4 |

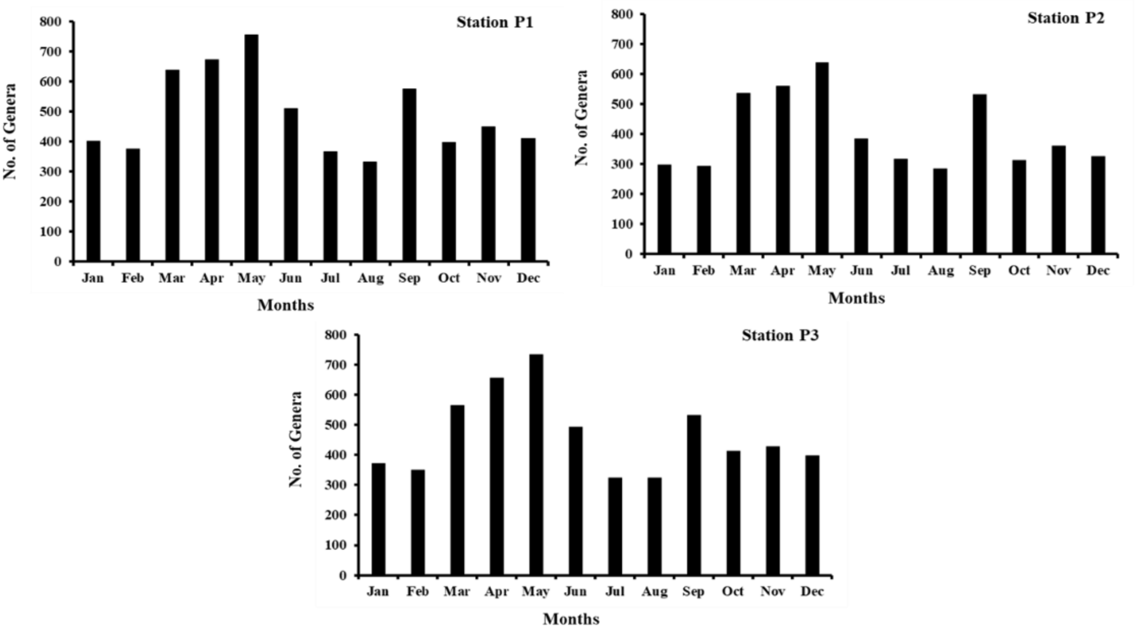
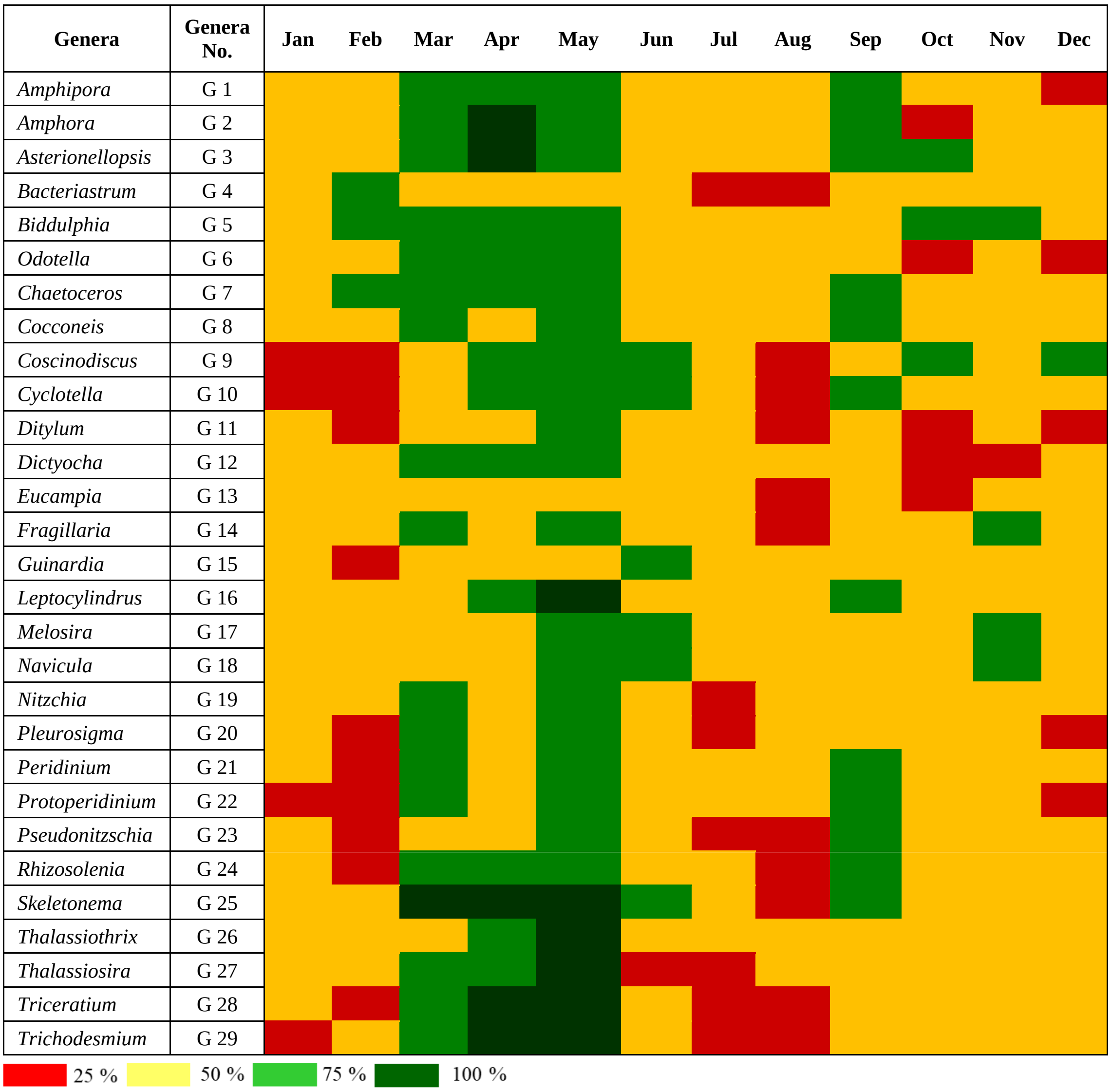


**Figure 2.** Monthly variations in no of phytoplankton genera

**Table 4.** List of dominant and common phytoplankton genera recorded at station P1



| Genera | Genera No. | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Amphipora* | G 1 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟥 |
| *Amphora* | G 2 | 🟨 | 🟨 | 🟩 | ⬛ | 🟩 | 🟨 | 🟨 | 🟨 | 🟩 | 🟥 | 🟨 | 🟨 |
| *Asterionellopsis* | G 3 | 🟨 | 🟨 | 🟩 | ⬛ | 🟩 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 | 🟨 | 🟨 |
| *Bacteriastrum* | G 4 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Biddulphia* | G 5 | 🟨 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 | 🟨 |
| *Odotella* | G 6 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟨 | 🟥 |
| *Chaetoceros* | G 7 | 🟨 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 |
| *Cocconeis* | G 8 | 🟨 | 🟨 | 🟩 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 |
| *Coscinodiscus* | G 9 | 🟥 | 🟥 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟥 | 🟨 | 🟩 | 🟨 | 🟩 |
| *Cyclotella* | G 10 | 🟥 | 🟥 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟥 | 🟩 | 🟨 | 🟨 | 🟨 |
| *Ditylum* | G 11 | 🟨 | 🟥 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟥 | 🟨 | 🟥 | 🟨 | 🟥 |
| *Dictyocha* | G 12 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 |
| *Eucampia* | G 13 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟨 | 🟥 | 🟨 | 🟨 |
| *Fragillaria* | G 14 | 🟨 | 🟨 | 🟩 | 🟨 | 🟩 | 🟨 | 🟨 | 🟥 | 🟨 | 🟨 | 🟩 | 🟨 |
| *Guinardia* | G 15 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Leptocylindrus* | G 16 | 🟨 | 🟨 | 🟨 | 🟩 | ⬛ | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 |
| *Melosira* | G 17 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 |
| *Navicula* | G 18 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 |
| *Nitzchia* | G 19 | 🟨 | 🟨 | 🟩 | 🟨 | 🟩 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Pleurosigma* | G 20 | 🟨 | 🟥 | 🟩 | 🟨 | 🟩 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 |
| *Peridinium* | G 21 | 🟨 | 🟥 | 🟩 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 |
| *Protoperidinium* | G 22 | 🟥 | 🟥 | 🟩 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟥 |
| *Pseudonitzschia* | G 23 | 🟨 | 🟥 | 🟨 | 🟨 | 🟩 | 🟨 | 🟥 | 🟥 | 🟩 | 🟨 | 🟨 | 🟨 |
| *Rhizosolenia* | G 24 | 🟨 | 🟥 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟥 | 🟩 | 🟨 | 🟨 | 🟨 |
| *Skeletonema* | G 25 | 🟨 | 🟨 | ⬛ | ⬛ | ⬛ | 🟩 | 🟨 | 🟥 | 🟩 | 🟨 | 🟨 | 🟨 |
| *Thalassiothrix* | G 26 | 🟨 | 🟨 | 🟨 | 🟩 | ⬛ | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Thalassiosira* | G 27 | 🟨 | 🟨 | 🟩 | 🟩 | ⬛ | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Triceratium* | G 28 | 🟨 | 🟥 | 🟩 | ⬛ | ⬛ | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Trichodesmium* | G 29 | 🟥 | 🟨 | 🟩 | ⬛ | ⬛ | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |

🟥 25 % 🟨 50 % 🟩 75 % ⬛ 100 %

*Chaetoceros* showed a decrease in growth rate where temperature increased from 28°C to 40°C. On the other hand, amphora demonstrated stable growth rate between 28 and 33°C, beyond which a slight reduction was observed at P2 due to increased temperature (above 33°C). Diatoms dominated the phytoplankton and there was no indication of any dominance by cyanobacteria or other harmful algal species, as a result of the thermal discharge. Though a measurable reduction in chlorophyll a was observed at station P2, the changes were no longer discernible a short distance beyond the mixing point. Chlorophyll-a and phytoplankton distribution were invariably reduced about 35% –70% at station P2 and the mixing point 15% – 50% lower as compared to the station P1 (Table 4 to 6). Most of the months, phytoplankton community was not affected by the thermal discharge from the power station except few occasions its exposed reduction in station P3. High numbers of *Asterionella, Skeletonema, Thalassionema, Thalassiothrix and Trichodesmium* were noticed all time except monsoon season in all stations, indicating their thermophilic nature.

**Table 5.** List of dominant and common phytoplankton genera recorded at station P2

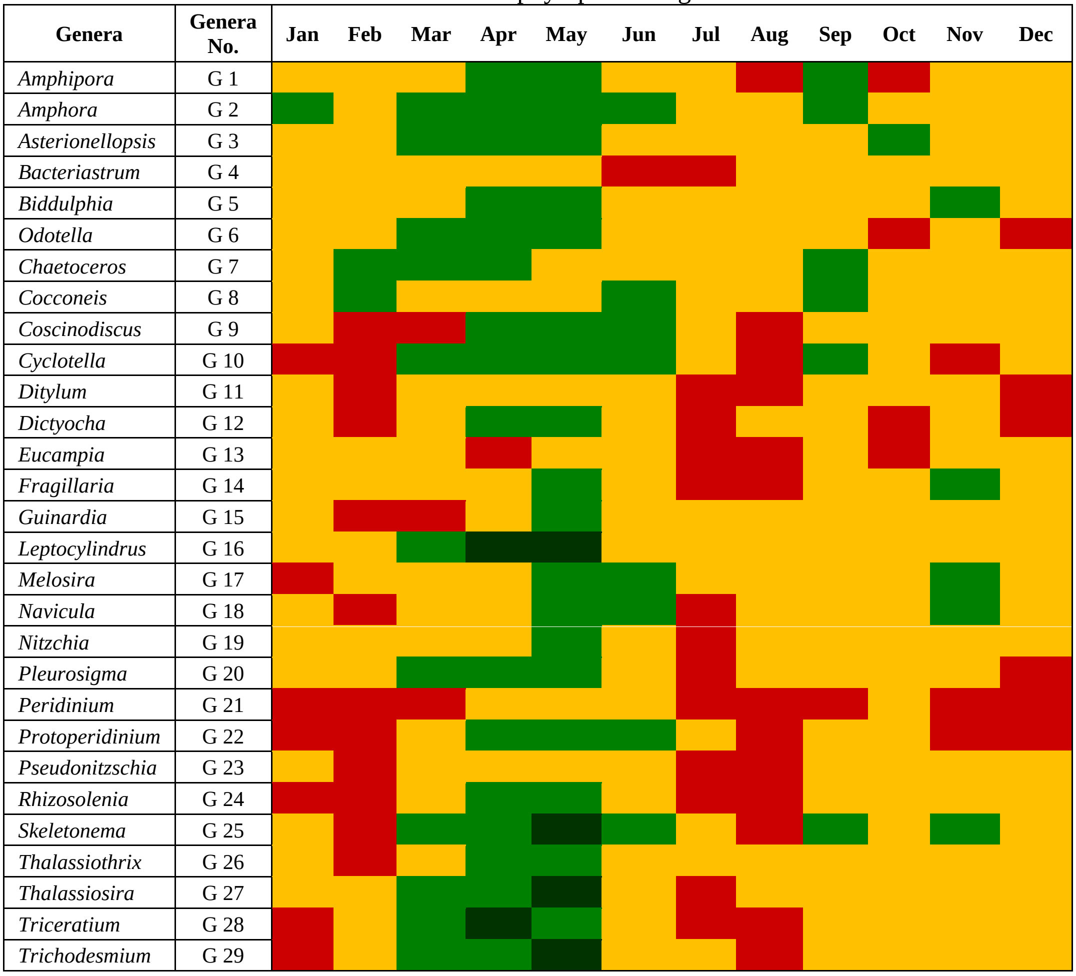
| Genera | Genera No. | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Amphipora* | G 1 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 | 🟨 | 🟥 | 🟥 | 🟨 |
| *Amphora* | G 2 | 🟨 | 🟥 | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟥 | 🟩 | 🟥 | 🟨 | 🟩 |
| *Asterionellopsis* | G 3 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Bacteriastrum* | G 4 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 | 🟨 | 🟥 | 🟥 | 🟥 |
| *Biddulphia* | G 5 | 🟨 | 🟥 | 🟨 | 🟩 | 🟩 | 🟨 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Odotella* | G 6 | 🟥 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟥 | 🟩 | 🟥 | 🟥 | 🟥 |
| *Chaetoceros* | G 7 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 | 🟥 | 🟨 | 🟨 |
| *Cocconeis* | G 8 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟨 | 🟥 | 🟨 | 🟥 |
| *Coscinodiscus* | G 9 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Cyclotella* | G 10 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 | 🟨 | 🟥 | 🟥 | 🟨 | 🟥 | 🟨 | 🟨 |
| *Ditylum* | G 11 | 🟥 | 🟥 | 🟥 | 🟨 | 🟩 | 🟨 | 🟥 | 🟥 | 🟨 | 🟥 | 🟥 | 🟥 |
| *Dictyocha* | G 12 | 🟥 | 🟥 | 🟨 | 🟩 | 🟩 | 🟨 | 🟥 | 🟥 | 🟩 | 🟥 | 🟥 | 🟥 |
| *Eucampia* | G 13 | 🟨 | 🟥 | 🟨 | 🟥 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 | 🟥 | 🟥 | 🟥 |
| *Fragillaria* | G 14 | 🟨 | 🟥 | 🟨 | 🟥 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Guinardia* | G 15 | 🟥 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟨 | 🟥 | 🟨 | 🟥 |
| *Leptocylindrus* | G 16 | 🟥 | 🟨 | 🟨 | 🟩 | ⬛ | 🟨 | 🟨 | 🟥 | 🟨 | 🟥 | 🟨 | 🟥 |
| *Melosira* | G 17 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Navicula* | G 18 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Nitzchia* | G 19 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Pleurosigma* | G 20 | 🟥 | 🟥 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 |
| *Peridinium* | G 21 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 |
| *Protoperidinium* | G 22 | 🟥 | 🟥 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟥 | 🟨 | 🟥 | 🟨 | 🟥 |
| *Pseudonitzschia* | G 23 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 | 🟥 | 🟨 | 🟥 |
| *Rhizosolenia* | G 24 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟨 | 🟥 | 🟥 | 🟨 |
| *Skeletonema* | G 25 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟥 | 🟩 | 🟨 | 🟨 | 🟥 |
| *Thalassiothrix* | G 26 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 |
| *Thalassiosira* | G 27 | 🟨 | 🟨 | 🟩 | ⬛ | ⬛ | 🟥 | 🟨 | 🟨 | 🟩 | 🟥 | 🟨 | 🟥 |
| *Triceratium* | G 28 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟥 | 🟩 | 🟥 | 🟥 | 🟨 |
| *Trichodesmium* | G 29 | 🟥 | 🟥 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟥 | 🟩 | 🟨 | 🟥 | 🟨 |

🟥 25 % 🟨 50 % 🟩 75 % ⬛ 100 %

## Relationships between phytoplankton and environmental variables via canonical correspondence analysis

Phytoplankton community changes were identified through CCA biplot which is responsible for important environmental variables are presented in Fig.3 and Fig. 4. In station P1, axis 1 and 2 explained the variability in the monthly genera environment biplot (Fig. 3). Salinity and temperature had positive correlation in axis 1 and highly associated with post monsoon. The variable that positively correlated in axis 2 were DO, turbidity, SPM and pH, chlorophyll a had a negative correlation in the same axis linked with summer. Genera like *Amphipora*, *Leptocylindrus*, *Dictyocha* and *Triceratium* found to have the positive correlation with salinity and temperature in axis 1 (Fig. 4). Chlorophyll-a was a positive relationship in axis 2, it explained the closer association with *Asterionellopsis*, *Biddulphia*, *Cocconeis*, *Coscinodiscus*, *Eucampia*, *Fragillaria*, *Pseudonitzschia*. However, some genera were negatively correlated in axis 2 with pH, DO and SPM (*Guinardia*, *Ditylum* and *Peridinium*).

**Table 6.** List of dominant and common phytoplankton genera recorded at station P3



| **Genera** | **Genera No.** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Amphipora* | G 1 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 | 🟨 | 🟨 | 🟥 | 🟩 | 🟥 | 🟨 | 🟨 |
| *Amphora* | G 2 | 🟩 | 🟨 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 |
| *Asterionellopsis* | G 3 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 |
| *Bacteriastrum* | G 4 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Biddulphia* | G 5 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 |
| *Odotella* | G 6 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟨 | 🟥 |
| *Chaetoceros* | G 7 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 |
| *Cocconeis* | G 8 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 |
| *Coscinodiscus* | G 9 | 🟨 | 🟥 | 🟥 | 🟩 | 🟩 | 🟩 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Cyclotella* | G 10 | 🟥 | 🟥 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 | 🟥 | 🟩 | 🟨 | 🟥 | 🟨 |
| *Ditylum* | G 11 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟥 |
| *Dictyocha* | G 12 | 🟨 | 🟥 | 🟨 | 🟩 | 🟩 | 🟨 | 🟥 | 🟨 | 🟨 | 🟥 | 🟨 | 🟥 |
| *Eucampia* | G 13 | 🟨 | 🟨 | 🟨 | 🟥 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 | 🟥 | 🟨 | 🟨 |
| *Fragillaria* | G 14 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟩 | 🟨 |
| *Guinardia* | G 15 | 🟨 | 🟥 | 🟥 | 🟨 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Leptocylindrus* | G 16 | 🟨 | 🟨 | 🟩 | ⬛ | ⬛ | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Melosira* | G 17 | 🟥 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 |
| *Navicula* | G 18 | 🟨 | 🟥 | 🟨 | 🟨 | 🟩 | 🟩 | 🟥 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 |
| *Nitzchia* | G 19 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Pleurosigma* | G 20 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 |
| *Peridinium* | G 21 | 🟥 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 | 🟨 | 🟥 | 🟥 |
| *Protoperidinium* | G 22 | 🟥 | 🟥 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 | 🟥 | 🟨 | 🟨 | 🟥 | 🟥 |
| *Pseudonitzschia* | G 23 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Rhizosolenia* | G 24 | 🟥 | 🟥 | 🟨 | 🟩 | 🟩 | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Skeletonema* | G 25 | 🟨 | 🟥 | 🟩 | 🟩 | ⬛ | 🟩 | 🟨 | 🟥 | 🟩 | 🟨 | 🟩 | 🟨 |
| *Thalassiothrix* | G 26 | 🟨 | 🟥 | 🟨 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Thalassiosira* | G 27 | 🟨 | 🟨 | 🟩 | 🟩 | ⬛ | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Triceratium* | G 28 | 🟥 | 🟨 | 🟩 | ⬛ | 🟩 | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| *Trichodesmium* | G 29 | 🟥 | 🟨 | 🟩 | 🟩 | ⬛ | 🟨 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |

Fig. 3 displays pH, chlorophyll-a temperature salinity in axis 1 and DO in axis 2 had positive correlations in station P2 CCA biplot, implying the influence of freshwater contribution during northeast monsoon. Whereas DO and SPM showed a significant negative correlation in axis 1. Turbidity and chlorophyll-a showed a negative and positive correlation in axis 1 and 2 with few genera of phytoplankton. Genera such as *Cocconeis, Eucampia, Fragillaria, Guinardia, Nitzchia* were positively correlated with SPM, DO, pH in axis 1 (Fig. 4). In axis 2 most of the genera were in negative correlation with *Chaetoceros, Guinardia, Skeletonema, Thalassiosira, Trichodesmium*. This pattern shows that less salinity and temperature results in unusual range and richness of phytoplankton.

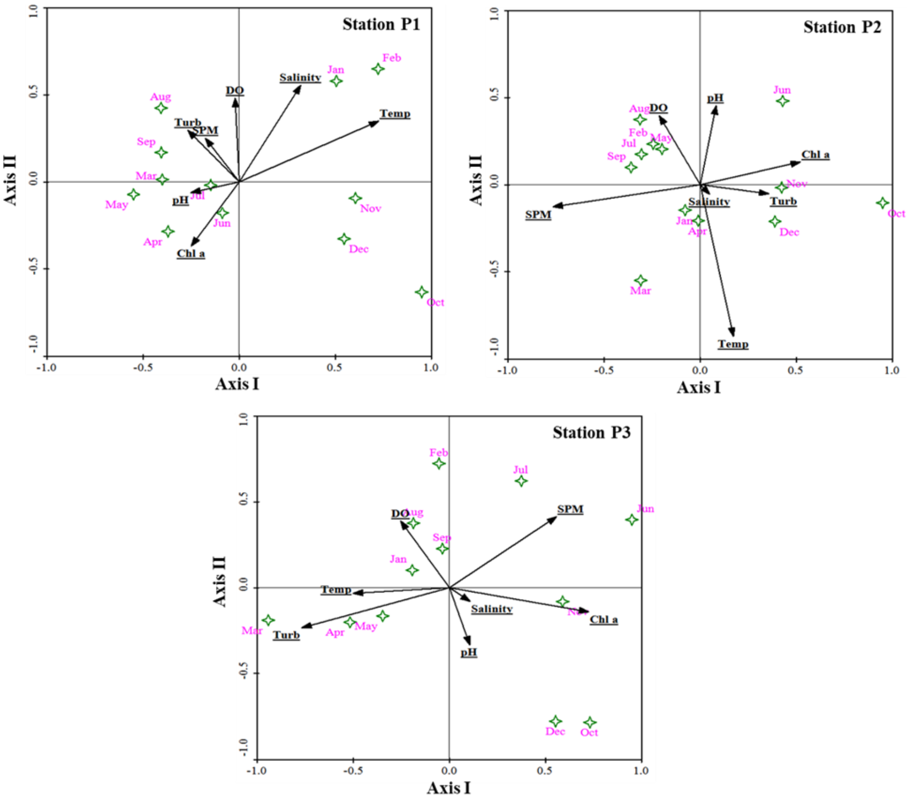


**Figure 3.** CCA for months Vs environmental variables at different stations (Genus numbers refer to Table 4)

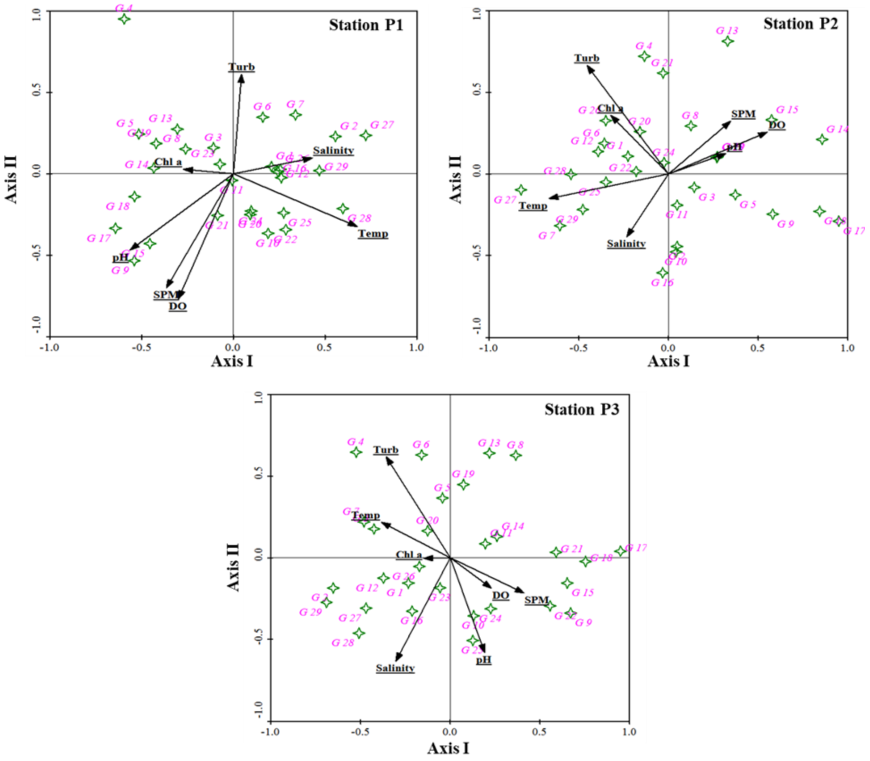


**Figure 4.** CCA for phytoplankton genera Vs environmental variables at different stations (Genus numbers refer to Table 4)

As for station P3, the main environmental parameters which had a positive correlation with axis 1 were SPM, chlorophyll-a, salinity and pH during northeast monsoon. During summer, temperature, DO and turbidity were negatively related (Fig. 3). pH, SPM, DO found to have the positive relation with *Cyclotella*, *Protoperidinium*, *Pseudonitzschia*, *Rhizosolenia* in axis 1 and few genera of phytoplankton (*Asterionellopsis*, *Chaetoceros*, *Pleurosigma*) were negatively correlated with turbidity and temperature in the same axis. Turbidity and temperature showed a negative and positive correlation in axis 1 and 2. Salinity showed a negative correlation in axis 2 for few genera of phytoplankton and highly associated with *Leptocylindrus* and *Pseudonitzschia*.

## DISCUSSION

Environmental variables are important factors to determine the structure of phytoplankton communities in aquatic life. Moreover, thermal effluents from power plants may cause some effects on the phytoplankton community in coastal environment. In the present study we observed that notable difference in phytoplankton genera between the intake and outfall waters (Table 4 and 5). Temperature influences the coastal environment as the life of marine organisms and hydrographical parameters [21]. When the both units were under operation, the water temperature at condenser MAPS outfall had variation about 8 - 10°C increased than intake water (Table 3). Li et al. [13] also suggested that the outfall temperature was significantly higher than in the surrounding water of Daya Bay in China. Environmental factors such as wind force, freshwater inflow and atmospheric temperature may attribute monthly variations in temperature. MAPS thermal effluent formed a plume pattern that moves north, south and the offshore direction, depending on the direction and magnitude of the prevailing longshore current.

Maximum pH was observed during summer at station P3 might be due to the influence of seawater penetration and high biological activity [22] and occurrence of high photosynthetic activity [9]. Salinity plays a limiting factor in living organisms, dilution and evaporation in the faunal and floral diversity of coastal ecosystem [23]. Earlier studies on salinity showed similar variations as in the present investigation. Highest salinity during summer could be due to neritic water dominance and higher rate of evaporation [24] and [25], and reduced salinity may be the freshwater inflow, the rainfall and fluctuation in tides during northeast monsoon [26] and [21]. The pattern of turbidity variation showed that the surface runoff is not the dominant factor regulating turbidity of the seawater at this part of the Bay of Bengal; rather, the resuspension of surficial sediments by stirring action and currents may be the factor controlling it.

Throughout the study period, the dissolved oxygen showed clear monthly variations. Low DO recorded during summer, might be due to high temperature and biological activity [27] and [28] and high content of DO noticed in northeast monsoon could be freshwater input and occurrence of phytoplankton [29]. During primary production, the chlorophyll-a act as principle pigment in marine water. The elevated concentration of Chl-a was observed in transition period, Saravanane et al. [30] also reported that the availability of high nutrients in the nearshore waters during the transition periods which supports the growth of phytoplankton. The chlorophyll-a reduction occurs during the passage of cooling water from the intake to the outfall, since the mixing point (P3) did not show any significant change in chlorophyll-a concentration. This revealed that the effect of thermal discharges on phytoplankton is marginal and confined impact.

Noticeable monthly differences in population density were observed among phytoplankton communities is illustrated in Fig. 2. Phytoplankton abundance was low during northeast monsoon and this could be due to heavy rainfall, reduced salinity, temperature, pH and high turbidity [31] and [32] and high density observed during summer might be more stable hydrographical conditions. *Asterionella, Skeletonema, Thalassionema, Thalassiothrix* and *Trichodesmium* was higher abundance during the study period except monsoon season, indicating their thermophilic nature. Ei-Gindy and Dorghan [33] explained that phytoplankton and their growth depend on environmental factors, which are variable in different seasons and regions.

Lowest distribution of phytoplankton was observed in station P2 at ~ 0.5km from MAPS outfall. Li et al. [13] also reported that the influence of phytoplankton community by the nuclear power plant thermal discharge in the subtropical region. The reduction in abundance of phytoplankton was observed during monsoon period, which could be mainly attributed to the low saline water. Remarkably throughout the study, phytoplankton abundance was observed to be higher at station P1 when compared to station P2. Shiah et al. [34] explored weak phytoplankton due to thermal effluents and chlorination cause reduction in phytoplankton productivity. CCA is a good tool to comprehend the relationship between phytoplankton distribution in marine ecosystem and environment variable data are suitable [35]. CCA revealed the various environmental parameters and differentiation among phytoplankton genera (Fig. 4).

*Chaetoceros* is a common genus of marine planktonic diatoms. *Chaetoceros* showed a decrease in growth rate where temperature increased among the tested temperatures, 28°C was optimum for *Chaetoceros* growth [36]. Phytoplankton passing through the power plant cooling water system experience combined mechanical, chemical and thermal stresses, which vary in duration and magnitude, depending on the flow rate. Previous reports stated that mechanical stress as a possible cause of significant mortality in entrained organisms [37] and [38]. Mallin et al. [39] also observed that direct thermal effect of cooling water discharge on phytoplankton communities was either localized or non-significant, depending upon site specific circumstances. The results of the present study clearly showed that power plant-induced effect on phytoplankton is relatively quite localized. Coastal waters close to the plant discharge showed no reduction in phytoplankton, attributable to the power plant discharge. There is no significant difference of phytoplankton communities in outlet and intake regions [40]. Earlier studies on phytoplankton in the coastal waters of Kalpakkam showed that the general distribution was not affected by the discharge from the power station [41]. The outcomes of the present study will validate the findings of Choi et al. [42], wherein they concluded that marine organisms are sensitive indicators to investigate the impact of power plant thermal effluents on coastal environments.

## CONCLUSION

The present study summarizes the phytoplankton abundance, distribution and the relationship between physico-chemical parameters and phytoplankton around Madras Atomic Power Station in Kalpakkam. Of the three stations investigated, the population of phytoplankton and chlorophyll-a content were higher in the station P1 than in station P2 (at engineering canal). However, slight differences in genera richness and diversity were noticed in station P3. Salinity and turbidity played a significant role in phytoplankton composition and density. According to these observations, it suggests that the thermal effluents may affect the phytoplankton structure between the MAPS condenser outfall and intake regions. It is clearly showed from Canonical Correspondence Analysis that the physico-chemical parameters have significant variation between seasons and influence the phytoplankton diversity and abundance. From CCA biplot, it is clear that temperature, salinity, DO and Chl-a played a great role in phytoplankton growth and richness. Overall study gives a good outline of the phytoplankton community effects caused by the thermal effluent. From the above discussion, it is concluded that phytoplankton distribution in the Kalpakkam coastal waters are not affected by thermal discharge from power plant. This study provides basic knowledge of phytoplankton around MAPS and still more investigation was required about the study of ecological impact caused by thermal discharge.

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